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Relationship between Granger non-causality and network graph of state-space representations

Jozsa, Monika

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Mónika Józsa
Groningen
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Bibliography

- Amblard, P.-O. and Michel, O. J. J. (2013). The relation between Granger causality and directed information theory: A review. *Entropy*, 15(1):113–143.
- Anderson, B. D. O. and Moore, J. B. (1979). *Optimal Filtering*. Prentice-Hall, Englewood Cliffs, NJ.
- Barnett, L., Barrett, A. B., and Seth, A. K. (2009). Granger causality and transfer entropy are equivalent for Gaussian variables. *Phys. Rev. Lett.*, 103:238701.
- Barnett, L. and Seth, A. K. (2014). The MVGC multivariate Granger causality toolbox: A new approach to Granger-causal inference. *Journal of Neuroscience Methods*, 223:50–68.
- Barnett, L. and Seth, A. K. (2015). Granger causality for state space models. *Physical Review E*, 91(4):737–739.
- Bini, D., Iannazzo, B., and Meini, B. (2011). *Numerical Solution of Algebraic Riccati Equations*. Society for Industrial and Applied Mathematics.
- Bolognani, S., Bof, N., Michelotti, D., Muraro, R., and Schenato, L. (2013). Identification of power distribution network topology via voltage correlation analysis. In *52nd IEEE Conference on Decision and Control*, pages 1659–1664.
- Caines, P. (1988). *Linear Stochastic Systems*. Wiley series in probability and mathematical statistics. John Wiley & Sons.
- Caines, P. E. (1976). Weak and strong feedback free processes. *IEEE Transactions on Automatic Control*, 21(5):737–739.

- Caines, P. E. and Chan, C. (1975). Feedback between stationary stochastic processes. *IEEE Transactions on Automatic Control*, 20(4):498–508.
- Caines, P. E., Deardon, R., and Wynn, H. P. (2003). Conditional orthogonality and conditional stochastic realization. In Rantzer, A. and Byrnes, C. I., editors, *Directions in Mathematical Systems Theory and Optimization*, volume 286, pages 71–84. Springer Berlin Heidelberg.
- Caines, P. E., Deardon, R., and Wynn, H. P. (2009). Bayes nets of time series: Stochastic realizations and projections. In Pronzato, L. and Zhigljavsky, A., editors, *Optimal Design and Related Areas in Optimization and Statistics*, volume 28 of *Springer Optimization and Its Applications*, pages 155–166. Springer New York.
- Caines, P. E. and Wynn, H. P. (2007). An algebraic framework for bayes nets of time series. In Chiuso, A., Pinzoni, S., and Ferrante, A., editors, *Modeling, Estimation and Control*, volume 364 of *Lecture Notes in Control and Information Sciences*, pages 45–57. Springer Berlin.
- Chen, H. and Maciejowski, J. M. (2001). A new subspace identification method for bilinear systems. CB2 1PZ U.K.
- D’Alessandro, P., Isidori, A., and Ruberti, A. (1974). Realization and structure theory of bilinear dynamical systems. *SIAM Journal on Control*, 12(3):517–535.
- Dankers, A. G. (2014). *System Identification in Dynamic Networks*. PhD thesis, Delft University of Technology.
- David, O. (2011). fMRI connectivity, meaning and empiricism: Comments on: Roebroeck et al. The identification of interacting networks in the brain using fMRI: Model selection, causality and deconvolution. *NeuroImage*, 58(2):306 – 309.
- Desai, U. (1986). Realization of bilinear stochastic systems. *IEEE Transactions on Automatic Control*, 31(2):189–192.
- Dufour, J.-M. and Renault, E. (1998). Short run and long run causality in time series: Theory. *Econometrica*, 66(5):1099–1125.
- Eichler, M. (2005). A graphical approach for evaluating effective connectivity in neural systems. *Philosophical Transactions B*, 360:953–967.
- Eichler, M. (2007). Granger causality and path diagrams for multivariate time series. *Journal of Econometrics*, 137(2):334 – 353.
- Eichler, M. (2012). Graphical modelling of multivariate time series. *Probability Theory and Related Fields*, 153(1):233–268.

- Engle, R. F. and Granger, C. W. J. (1987). Co-integration and error correction: Representation, estimation, and testing. *Econometrica*, 55(2):251—276.
- Favoreel, W., Moor, B. D., and Overschee, P. V. (1999). Subspace identification of bilinear systems subject to white inputs. *IEEE Transactions on Automatic Control*, 44(6):1157–1165.
- Friston, K. J., Harrison, L., and Penny, W. (2003). Dynamic causal modeling. *Neuroimage*, 19(4):1273 – 1302.
- Gevers, M. R. and Anderson, B. (1982). On jointly stationary feedback-free stochastic processes. *IEEE Transactions on Automatic Control*, 27(2):431–436.
- Geweke, J. F. (1984). Measures of conditional linear dependence and feedback between time series. *Journal of the American Statistical Association*, 79(388):907–915.
- Gikhman, I. I. and Skorokhod, A. V. (2004). *The Theory of Stochastic Processes II*, volume 1 of *Classics in Mathematics*. Springer Berlin.
- Goebel, R., Roebroeck, A., Kim, D.-S., and Formisano, E. (2003). Investigating directed cortical interactions in time-resolved fMRI data using vector autoregressive modeling and Granger causality mapping. *Magnetic Resonance Imaging*, 21:1251–1261.
- Golub, H. G. and Van Loan, C. F. (2013). *Matrix computations*. The Johns Hopkins University Press.
- Gonçalves, J., Howes, R., and Warnick, S. (2007). Dynamical structure functions for the reverse engineering of lti networks. In *46th IEEE Conference on Decision and Control*, pages 1516–1522.
- Gonçalves, J. and Warnick, S. (2008). Necessary and sufficient conditions for dynamical structure reconstruction of LTI networks. *IEEE Transactions on Automatic Control*, 53(7):1670–1674.
- Granger, C. W. J. (1963). Economic processes involving feedback. *Information and Control*, 6(1):28–48.
- Granger, C. W. J. (1988). Some recent development in a concept of causality. *Journal of Econometrics*, 39(1):199 – 211.
- Hannan, E. J. and Deistler, M. (1988). *The Statistical Theory of Linear Systems*. Classics in Applied Mathematics. Society for Industrial and Applied Mathematics.

- Havlicek, M., Roebroek, A., Friston, K., Gardumi, A., Ivanov, D., and Uludag, K. (2015). Physiologically informed dynamic causal modeling of fMRI data. *Neuroimage*, 122:355–372.
- Howes, R., Eccleston, L., Gonçalves, J., Stan, G.-B., and Warnick, S. (2008). Dynamical structure analysis of sparsity and minimality heuristics for reconstruction of biochemical networks. In *47th IEEE Conference on Decision and Control*.
- Hsiao, C. (1982). Autoregressive modelling and causal ordering of econometric variables. *Journal of Economic Dynamics and Control*, 4:243–259.
- Jozsa, M., Petreczky, M., and Camlibel, M. K. (2016). Towards realization theory of interconnected linear stochastic systems. In *22nd International Symposium on Mathematical Theory of Networks and Systems*, pages 120–122.
- Jozsa, M., Petreczky, M., and Camlibel, M. K. (2017a). Causality based graph structure of stochastic linear state-space representations. In *56th IEEE Conference on Decision and Control*, pages 2442–2447.
- Jozsa, M., Petreczky, M., and Camlibel, M. K. (2017b). Relationship between causality of stochastic processes and zero blocks of their joint innovation transfer matrices. In *20th World Congress of the International Federation of Automatic Control*, pages 4954–4959.
- Jozsa, M., Petreczky, M., and Camlibel, M. K. (2018a). Causality and network graph in general bilinear state-space representations. *submitted to IEEE Transactions on Automatic Control*.
- Jozsa, M., Petreczky, M., and Camlibel, M. K. (2018b). Relationship between Granger non-causality and network graph of state-space representations. *IEEE Transactions on Automatic Control*.
- Julius, A. A., Zavlanos, M., Boyd, S., and Pappas, G. J. (2009). Genetic network identification using convex programming. *Systems Biology, IET*, 3:155–166.
- Kang, T., Moore, R., Li, Y., Sontag, E. D., and Bleris, L. (2015). Discriminating direct and indirect connectivities in biological networks. *National Academy of Sciences USA*, 112:12893–12898.
- Katayama, T. (2005). *Subspace Methods for System Identification*. Communications and Control Engineering. Springer London.
- Kempker, P. L. (2012). *Coordination Control of Linear Systems*. PhD thesis, Amsterdam: Vrije Universiteit.

- Kempker, P. L., Ran, A. C. M., and van Schuppen, J. H. (2014a). Construction and minimality of coordinated linear systems. *Linear Algebra and its Applications*, 452:202–236.
- Kempker, P. L., Ran, A. C. M., and van Schuppen, J. H. (2014b). LQ control for coordinated linear systems. *IEEE Transactions on Automatic Control*, 59(4):851–862.
- Kramer, G. (1998). *Directed information for channels with feedback*. PhD thesis, Swiss Federal Institute of Technology Zürich.
- L. Massey, J. (1990). Causality, feedback and directed information. In *International Symposium on Information Theory and its Applications*, pages 27–30.
- Larimore, W. E. (1983). System identification, reduced-order filtering and modeling via canonical variate analysis. In *American Control Conference*.
- Lindquist, A. and Picci, G. (2015). *Linear Stochastic Systems*, volume 1 of *Series in Contemporary Mathematics*. Springer Berlin.
- Ljung, L. (1999). *System Identification: Theory for the User*. Communications and Control Engineering. Prentice Hall PTR, 2nd edition.
- Lütkepohl, H. (1993). Testing for causation between two variables in higher-dimensional var models. In Schneeweiß, H. and Zimmermann, K. F., editors, *Studies in Applied Econometrics*, Contributions to Economics, pages 75–91. Physica HD.
- Monshizadeh, N., Trentelman, H. L., and Camlibel, M. K. (2014). Projection based model reduction of multi-agent systems using graph partitions. *IEEE Transactions on Control of Network Systems*, 1(2):145–154.
- Nordling, T. E. M. and Jacobsen, E. W. (2011). On sparsity as a criterion in reconstructing biochemical networks. In *18th IFAC World Congress*.
- Pambakian, N. (2011). LQG coordination control. Master’s thesis, Delft University of Technology.
- Papana, A., Kyrtsou, K., Kugiumtzis, D., and Diks, C. G. H. (2014). Identifying causal relationships in case of non-stationary time series. CeNDEF Working Papers 14-09, Universiteit van Amsterdam, Center for Nonlinear Dynamics in Economics and Finance.
- Pearl, J. (2000). *Causality: Models, Reasoning and Inference*. Cambridge University Press, 1st edition.

- Penny, W., Stephan, K. E., Mechelli, A., and Friston, K. J. (2004). Comparing dynamic causal models. *NeuroImage*, 22(3):1157 – 1172.
- Petreczky, M. and René, V. (2017). Realization theory for a class of stochastic bilinear systems. *IEEE Transactions on Automatic Control*, 63(1):69–84.
- Ran, A. C. M. and van Schuppen, J. H. (2014). Coordinated linear systems. In *Coordination Control of Distributed Systems*, volume 456 of *Lecture Notes in Control and Information Sciences*, pages 113–121.
- Roebroeck, A., Formisano, E., and Goebel, R. (2011a). The identification of interacting networks in the brain using fmri: Model selection, causality and deconvolution. *NeuroImage*, 58(2):296 – 302.
- Roebroeck, A., Formisano, E., and Goebel, R. (2011b). Reply to friston and david: After comments on: The identification of interacting networks in the brain using fmri: Model selection, causality and deconvolution. *NeuroImage*, 58(2):310–311.
- Roebroeck, A., Seth, A. K., and Valdes-Sosa, P. A. (2011c). Causal time series analysis of functional magnetic resonance imaging data. *Journal of Machine Learning Research, Proceedings Track*, 12:65–94.
- Rosenbrock, H. H. (1970). *State-Space and Multivariable Theory*. John Wiley.
- Rozanov, Y. A. (1987). *Introduction to Random Processes*. Classics in Mathematics. Springer Berlin.
- Sandberg, H. and Murray, R. M. (2009). Model reduction of interconnected linear systems. *Optimal Control Applications and Methods*, 30(3):225–245.
- Solo, V. (2016). State-space analysis of Granger-Geweke causality measures with application to fMRI. *Neural Computation*, 28:914 –949.
- Trentelman, H. L., Stoorvogel, A. A., and Hautus, M. (2001). *Control theory for linear systems*. Communications and Control Engineering. Springer London.
- Triacca, U. (2000). On the Hsiao definition of non-causality. *Economics Letters*, 66:261–264.
- Valdes-Sosa, P. A., Roebroeck, A., Daunizeau, J., and Friston, K. J. (2011). Effective connectivity: Influence, causality and biophysical modeling. *Neuroimage*, 58(2):339–361.

- Van den Hof, P. M. J., Dankers, A., Heuberger, P. S. C., and Bombois, X. (2013). Identification of dynamic models in complex networks with prediction error methods—basic methods for consistent module estimates. *Automatica*, 49(10):2994–3006.
- van der Schaft, A. J. (2015). Physical network systems and model reduction. In Belur, M. N., Camlibel, M. K., Rapisarda, P., and Scherpen, J. M., editors, *Mathematical Control Theory II: Behavioral Systems and Robust Control*, pages 199–219. Springer, Cham.
- Van Overschee, P. and De Moor, B. (1996). *Subspace Identification for Linear System: Theory - Implementation - Applications*. Kluwer Academic Publishers.
- Weerts, H. H. M. (2018). *Identifiability and Identification Methods for Dynamic Networks*. PhD thesis, Eindhoven University of Technology.
- Weerts, H. H. M., Van den Hof, P. M. J., and Dankers, A. G. (2018). Identifiability of linear dynamic networks. *Automatica*, 89:247–258.
- Westra, R., Hollanders, G., and Tuyls, K. (2007). The identification of dynamic gene-protein networks. *Springer Lecture Notes in Bioinformatics*, 4366:157–171.
- Wiener, N. (1956). The theory of prediction. In Beckenham, E. F., editor, *Modern mathematics for engineers, Series I*.
- Yuan, Y., Glover, K., and Gonçalves, J. (2015). On minimal realisations of dynamical structure functions. *Automatica*, 55:159–164.
- Yuan, Y., Stan, G.-B., Warnick, S., and Gonçalves, J. (2011). Robust dynamical network structure reconstruction. *Automatica*, 47(6):1230–1235.
- Yue, Z., Thunberg, J., Yuan, Y., and Gonçalves, J. (2015). Dynamical structure function and Granger causality: Similarities and differences. In *54th IEEE Conference on Decision and Control*, pages 889–894.
- Zhang, W., Liu, W., Zang, C., and Liu, L. (2017). Multi-agent system based integrated solution for topology identification and state estimation. *IEEE Transactions on Industrial Informatics*, 13(2):714–724.